EXAMPLES OF GROUND-PENETRATING RADAR PROFILES

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Summary

Ground-penetrating radar can provide essentially continuous profiles of dielectric interfaces within soil, rock, building materials, water, or ice. Radar is particularly suited to the location of air-filled voids, and examples are provided of voids in soil and rock, and under pavements. Radar can map buried pipes and several profiles illustrate this application. Stratification within soil and rock can be very distinct; examples are provided of this and also the abrupt destratification which can sometimes be found at the edges of landfills.

Compared to other geophysical techniques, ground-penetrating radar typically has a shallower exploration depth. In clays, it usually does not exceed 5 ft, however in sands it can be 30 ft or more. Its profiling depth is greatest in materials having a high electrical resistivity and a resistivity sounding is a good test. Radar is not suitable for areas with saline soil.

Radar is an interface detector rather than a bulk detector, and this feature further delimits its applications. Weathering of bedrock can make its boundary with the overlying soil diffuse and graded; in this case, it can be undetectable on radar profiles.
The water table in fine-grained soils can also be diffuse and undetectable.

Blue text marks hyperlinks to the figures.

Introduction

Ground-penetrating radar is a true radar system. It differs from most other radars primarily by having its signal beamed into the earth rather than the air. Contrasts in the electrical properties of materials in the earth cause reflections of the radar signal. By moving the radar antenna, the spatial pattern of these reflections is determined. The resulting radar profile is a fair approximation of the shape of the underground materials.

Radar can sometimes detect a variety of different objects: voids, filled with air or water; metals, wires, and pipes; wood, plastic, ceramic, and stone; ice lenses and the water table; and changes in the stratification of the earth and rock. The identification of these materials is estimated primarily from the three-dimensional form which is revealed by a group of radar profiles.

Radar can profile through earth, stone, water, ice, snow, air, and building materials. It cannot profile through metals, either continuous metals or metal mesh. It is possible to make radar profiles through reinforced concrete; as the spacing between metal bars is reduced, the distance which can be profiled past the bars is also reduced.

A Radar System

The ground-penetrating radar which has furnished the examples here is a SIR System-7, designed and manufactured by Geophysical Survey Systems, Inc. (15 Flagstone Drive, Hudson, New Hampshire). A description of an earlier, but related, radar system has been given by Morey (1974).

The radar antennas are all mounted in rectangular boxes about 1-3 ft in size and are pulled along the ground with the aid of wheels or skids, typically at a speed of between 0.5 and 5 miles per hour. The antenna boxes also contain much of the electronics of the radar transmitter and receiver.

The radar pulse is about one and one-half cycles long. This short pulse has frequency components over a wide spectrum, but is characterized by a predominant frequency. Higher frequency allows greater depth resolution but lower frequency allows greater profiling depth. Several different radar antennas have generated the profiles here: a model 3055 antenna with a predominant frequency of about 120 MHz; a model 3105 antenna with a frequency of about 180 MHz; and a model 3102 antenna with a predominant frequency of about 315 MHz. These frequencies are listed with the figures. The peak radiated power from these antennas is only a few watts.

A sampling circuit within the receiver lowers the frequency to the audio range for

transmission along an electrical cable to control and recording instruments. A graphic recorder gives an immediate display of the ground profile as it is generated. The echoes can also be stored on a magnetic tape recorder for later analysis.

Radar echoes result from interfaces which have a contrast in either electrical resistivity or dielectric constant (permittivity). These physical quantities primarily determine two radar parameters: the attenuation and the velocity of propagation of the radar pulse.

The greatest disadvantage of radar is that only shallow profiles are possible in some soils. While sandy soils can allow deep profiles, clayey soils allow only shallow profiles. Salt is also a factor. Deicing salts from wintertime can cause high attenuation of the radar signals. The radar cannot profile through salt water and even inland lakes and rivers can have sufficiently conductive water that only shallow profiles can be made.

A measurement of electrical resistivity is a good predictor of profiling depth; the higher the resistivity, the deeper the profiles. A resistivity sounding can also indicate the stratification of the earth. Distinct stratification can reflect much of the radar signal and weaken deeper echoes. Distinct strata can be dessicated topsoils, rainfall percolation fronts, and pavements. The radar signal also reverberates within these layers, obscuring the echoes from just below.

The distance to reflectors on radar profiles is determined primarily by the echo delay time. This can be converted to apparent depth if the velocity of the radar pulse can be determined. If an object is at a known depth, the depths of other objects can be extrapolated. The hyperbolic geometry of echo arcs, such as those in Figure 1, can also furnish an estimate of depth and pulse velocity.

A common depth point sounding with separated transmitter and receiver antennas can also help to determine pulse velocity (Clough, 1976). The velocity of the radar pulse varies with position and also depth, with a strong dependence on the moisture content of the earth; the velocity values listed with the figures have been estimated for the region of interest on the profiles.

Several recent articles discuss the general principles of ground-penetrating radar and reference many of the earlier articles (Harmuth, 1981, p.30-46; Jackson, 1981, p.58-60; Chan, 1979).

Discussion of the Profile Examples

The radar profiles here have been selected to show different types of features as clearly as possible. The profiles are not typical ones. On the average profile, it is often difficult to isolate features because of complex echoes which can obscure them.

Pipes are an example. Figures 1 though 5 show pipes or similar lineaments. Pipes and wires can be traced by making radar profiles in a direction roughly perpendicular to

them. While these figures show isolated arcs from the utility lines, surrounding material, particularly in the backfilled trench, can cause echoes which hide the pipe or wire on some profiles.

These profiles have been printed with echo signals above a given threshold shown as black. High amplitude signals of either polarity are dark spots or bands with thin white lines between them. The unchanging black bands near the apparent surface are the effect of the transmitted pulse going directly to the receiver.

Radar is an excellent detector of voids. Sometimes they are indicated indirectly, as in Figure 5. However, large, small, deep, and shallow voids are directly seen in the profiles of Figures 6 through 9. Figure 8 shows a typical effect; the radar can profile more deeply into rock than soil. While the tops of cavities are easy to detect, their bottoms are seldom seen because the echoes from the two interfaces usually interfere.

An isolated rock in soil can cause a strong radar echo; see Figure 10. The form and amplitude of the echo are not necessarily different from that caused by a void. In principle, the phase of the echo within the pulse envelope can provide clues to distinguish metals, voids, and rocks. In practice, this is seldom possible.

The continuous profiles which the radar furnishes can be excellent maps of buried strata and Figures 11 through 15 are examples. Note that the horizontal scale is greatly compressed relative to the vertical scale on all of the profiles. This exaggerates the slopes of interfaces. Radar is best at profiling strata which have a shallow dip. Strata which dip at an angle of greater than 45° cannot be directly traced.

Radar is also good as an indicator of destratification. Should the earth be naturally stratified, a backfilled excavation can be detected. If the backfill material is intrusive debris, the radar can indicate it by a chaotic pattern. Figures 16 through 18 are examples. Radar can sometimes clearly map the edges of landfills and can sometimes suggest the depth to the top of the debris. It can seldom if ever map the depth to the bottom of a landfill because the extended reverberation of the radar pulse within the debris makes the landfill look thicker than it is.

The dielectric constant of water is much higher than that of other earth materials. However, the water table is usually difficult to detect because it is so diffuse in typical fine-grained soils. It is seen clearly in Figure 16 because of the sandy soil. The depth scale in this figure is not suitable below the water table; at the greater depths, the indicated depths should be approximately halved.

Conclusion

The big advantage of ground-penetrating radar is the rich detail which it provides of underground materials. Its greatest disadvantage is the shallow profiling depth which is all

too common in typical silty or clayey soils.

Radar is much better at detecting objects than identifying them. Like other geophysical techniques, it is best as an extrapolator from know conditions.

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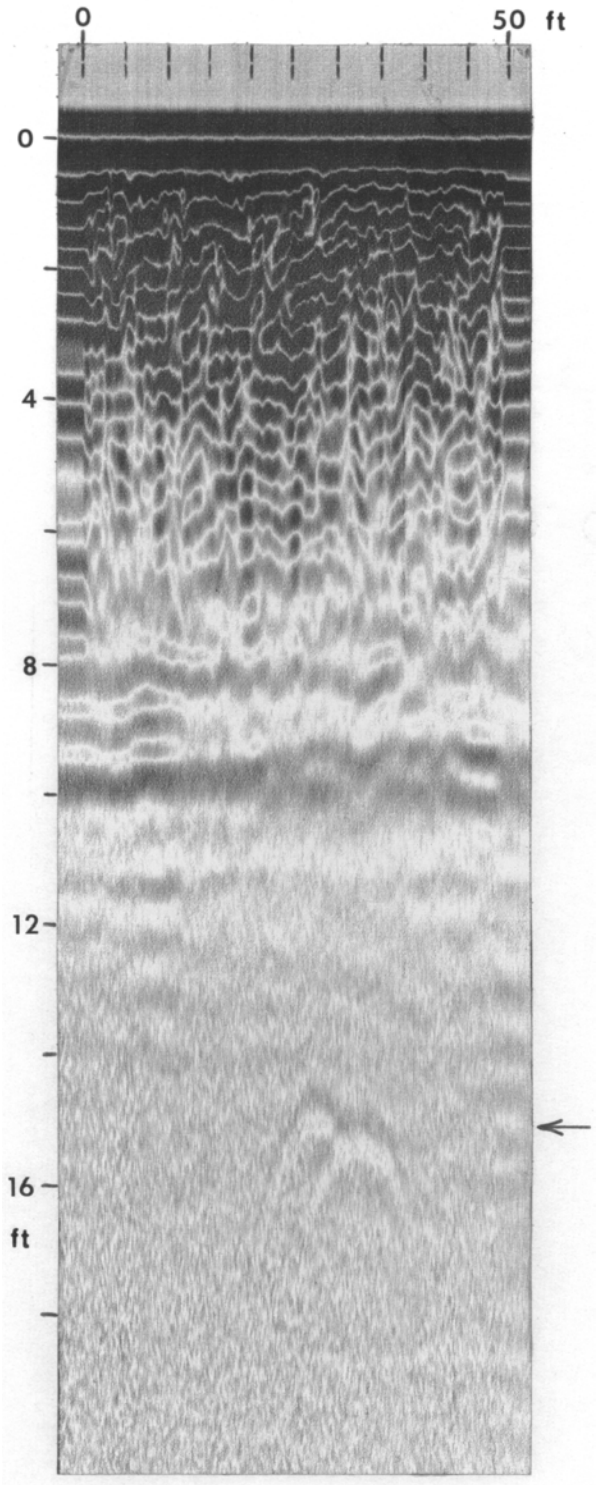

Figure 1: The two arcs at a depth of about 15 ft result from the radar echoes from a pair of steel pipes having a diameter of 20 inches. The grainy pattern toward the bottom of this soil profile is caused by electronic noise. The reflections from the two pipes are so strong that they can readily be detected even though the surrounding strata are not.

Frequency: 180 MHz
Pulse velocity: 0.24 ft/ns
Earth resistivity: Unknown; sandy soil

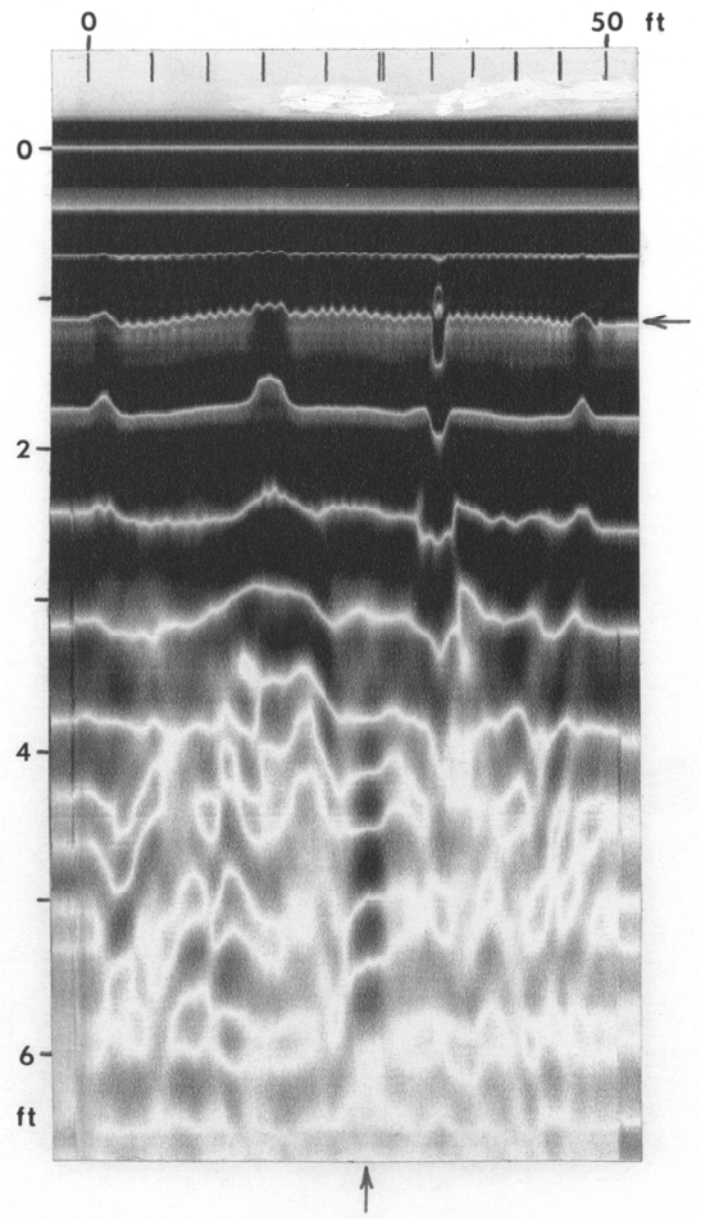

Figure 2: The dark spots at an apparent depth of 4-6 ft in the middle of this profile are echoes from a pipe buried below a reinforced concrete highway. The pipe is an 18 inch diameter culvert made of reinforced concrete. The undulations on the profile at an apparent depth of about 1 ft are caused by the reinforcing mesh in the 10 inch thick pavement; the spacing between metal rods is 1 ft.

Frequency: 120 MHz
Pulse velocity: 0.21 ft/ns
Earth resistivity: Unknown; clayey soil

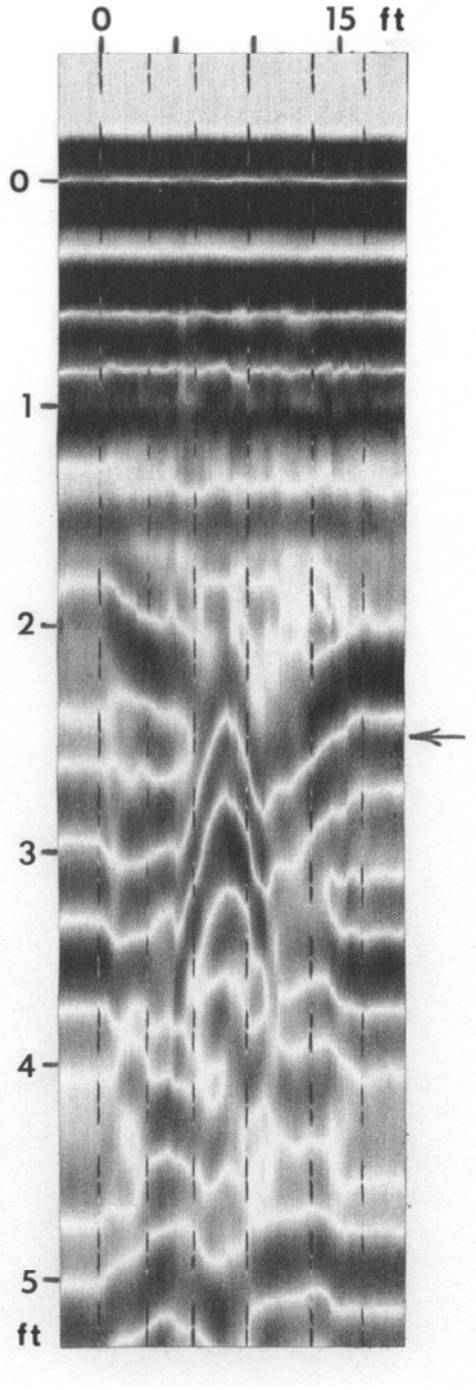

Figure 3: A buried wooden trough causes this pattern. Two planks in the form of an inverted V were found at a depth of 30 inches; this was probably a drain.

Frequency: 120 MHz
Pulse velocity: 0.18 ft/ns
Earth resistivity: 300 ohm-meter

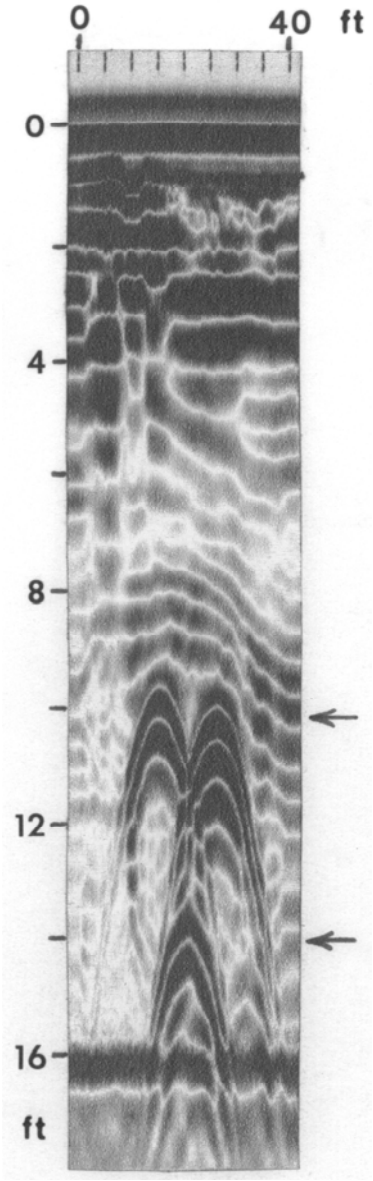

Figure 4: A pair of 8 ft diameter corrugated metal pipes cause the pair of echoes at a depth of 10 ft on this profile. The arc at an apparent depth of 14 ft is a spurious echo resulting from the radar pulse reflecting between the two pipes; the round trip echo delay time resulting from the two reflections is larger than that from a single, direct, reflection.

Frequency: 180 MHz
Pulse velocity: 0.34 ft/ns
Earth resistivity: Unknown; sandy soil

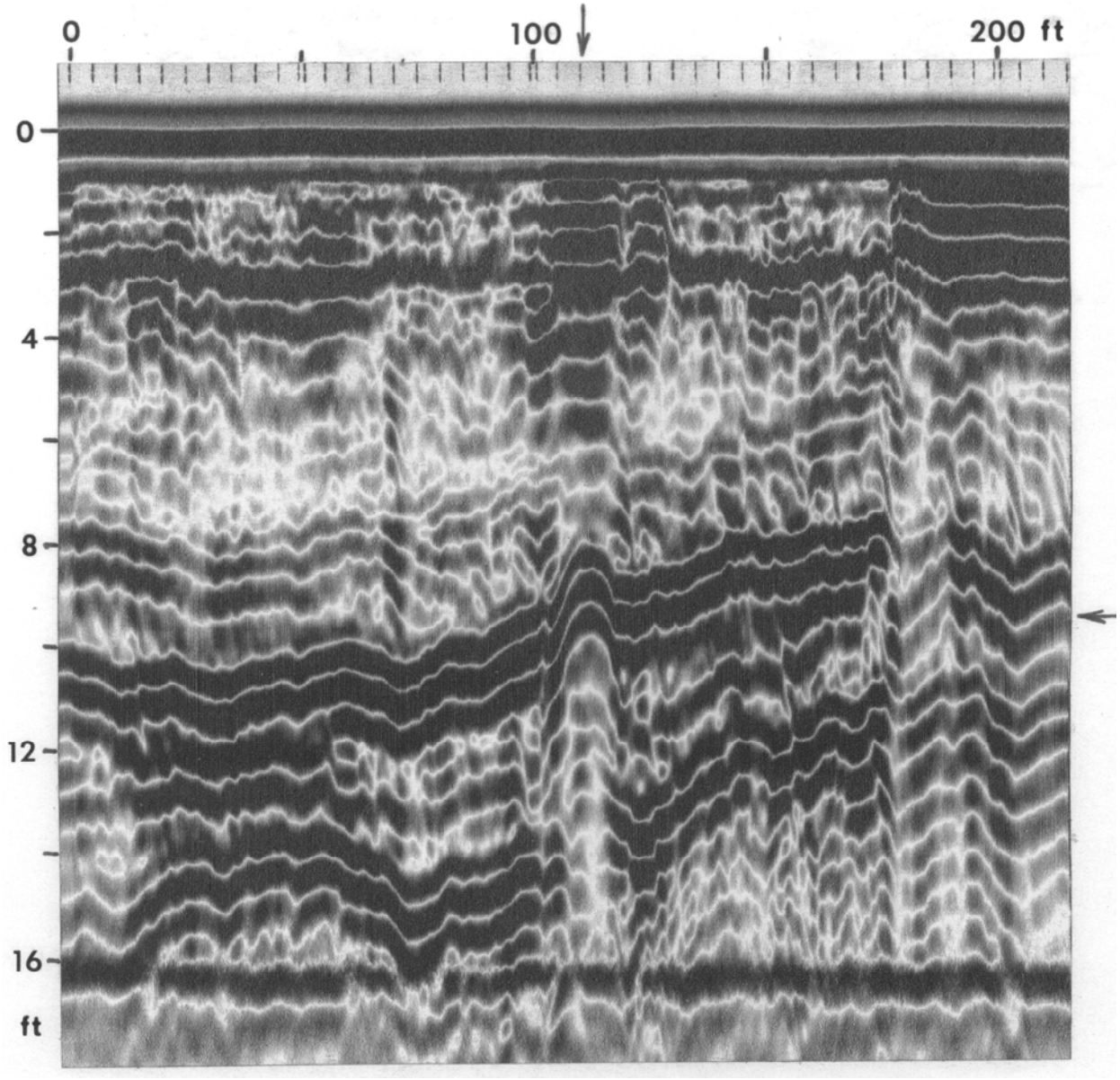

Figure 5: This radar profile was made along the length of the two pipes in Figure 4. The echo from the pipes is indicated by the dark bands at a depth of about 10 ft. Between the 105 and 115 ft points on this profile, the pipes appear to rise. This is the result of a 2 ft thick air void under the 18 inch thick concrete at the surface. The pipes' apparent depth decreases because the radar pulse travels faster in air than in soil. Figure 4 is a perpendicular profile at the 50 ft point on this profile.

Frequency: 180 MHz
Pulse velocity: 0.34 ft/ns
Earth resistivity: Unknown; sandy soil

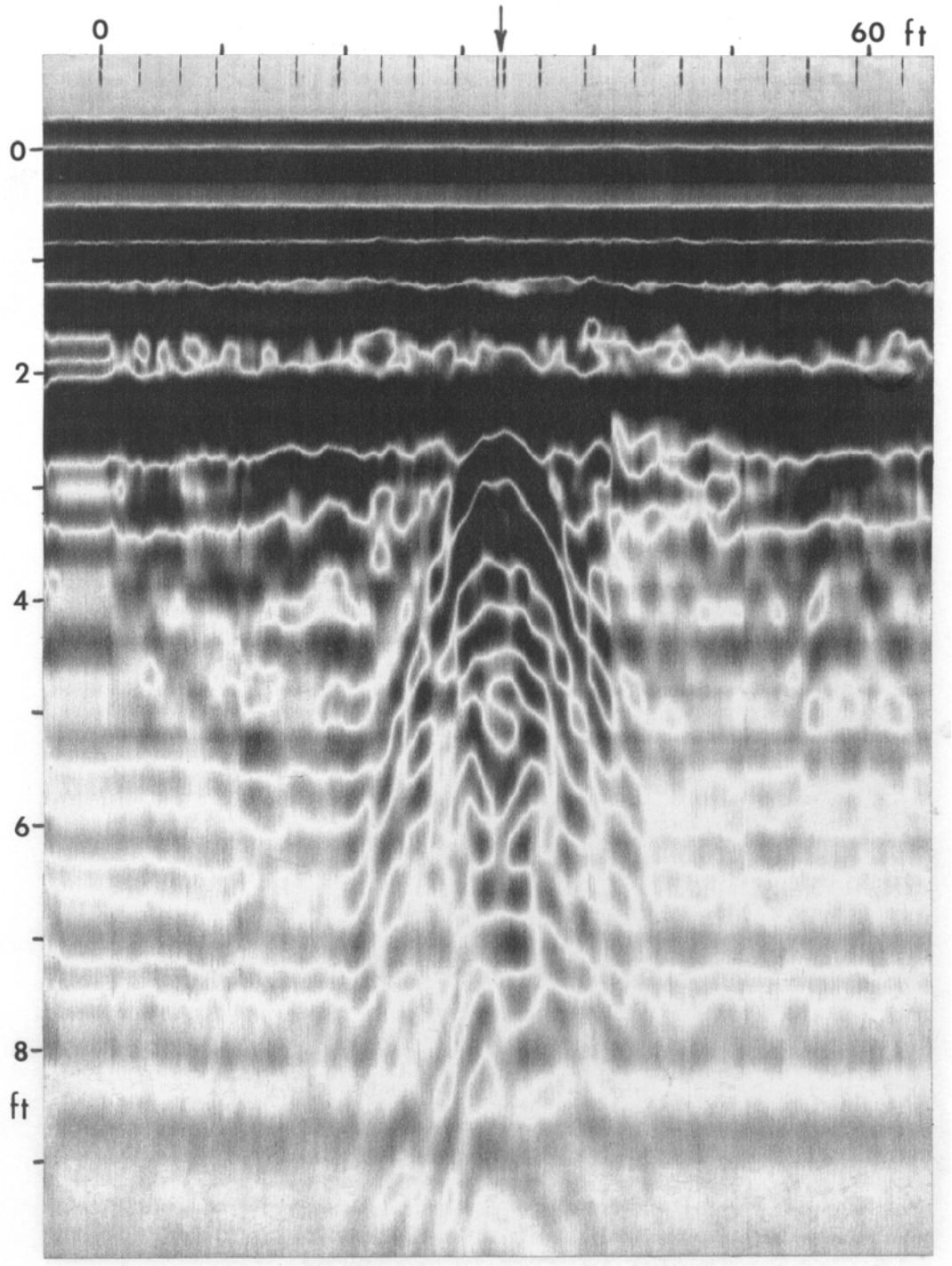

Figure 6: Air-filled voids yield a strong reflection of the radar pulse and are readily detectable. This distinctive echo is due to a vault which is 8.5 ft wide and has an arched stone roof.

Frequency: 120 MHz
Pulse velocity: 0.25 ft/ns
Earth resistivity: 125 ohm-meter

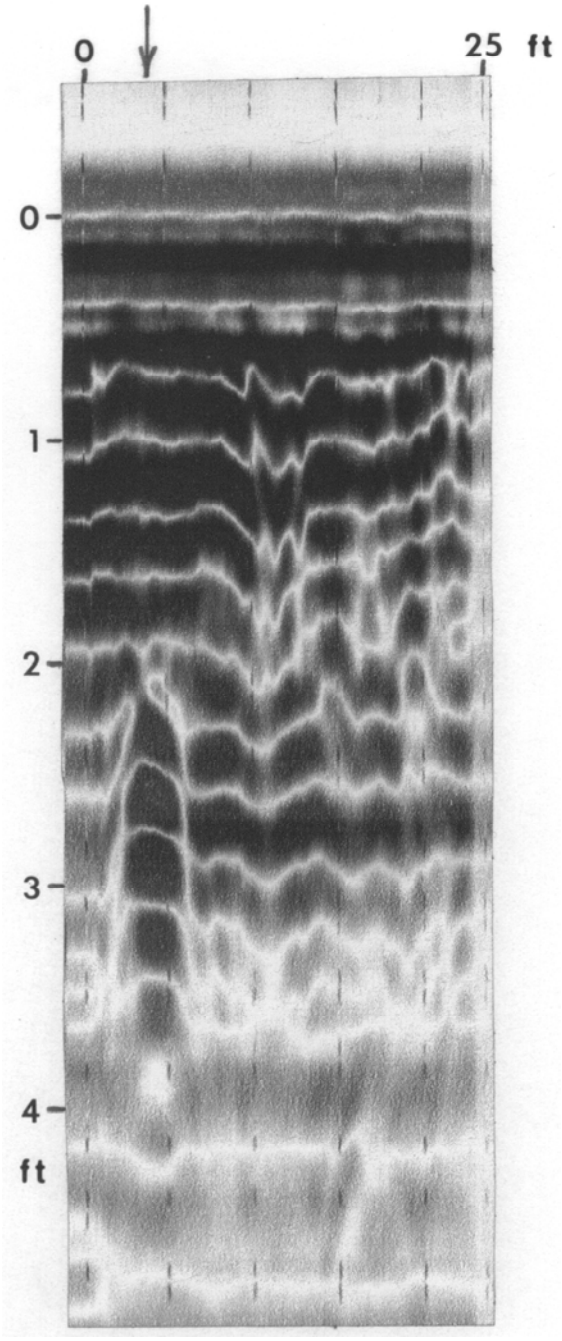

Figure 7: A small cavity in the soil causes the echo at a depth of 2.5 ft on the left side of this profile. This cavity was found to be about 10 inches high and 18 inches wide; it was probably a rodent's burrow or den.

Frequency: 180 MHz
Pulse velocity: 0.18 ft/ns
Earth resistivity: 100 ohm-meter

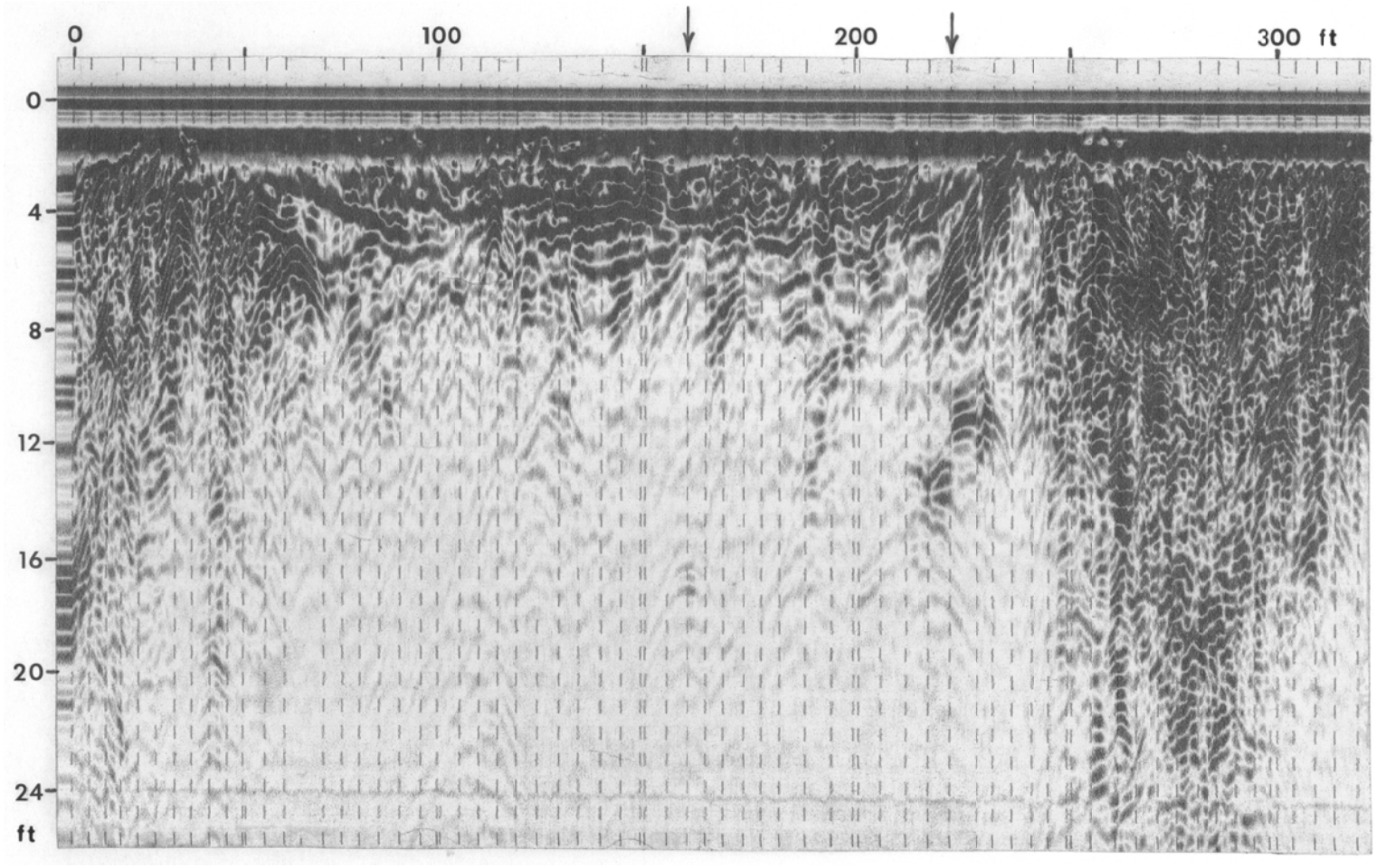

Figure 8: At the 160 ft point on this radar profile, an echo is seen at an apparent depth of 16 ft. This results from a cavern whose roof was found to vary between 9 ft and 14 ft underground. In the area between 50 ft and 225 ft on this profile, surface soils are indicated by horizontal stratification and the attenuation of deeper echoes. In the other areas of the profile, the soil is thin and the radar profiles deeply into the limestone below. The profile line passes next to an open sinkhole around the 220 ft point.

Frequency: 120 MHz
Pulse velocity: 0.25 ft/ns
Earth resistivity: 100 ohm-meter (soil); 350 ohm-meter (rock)

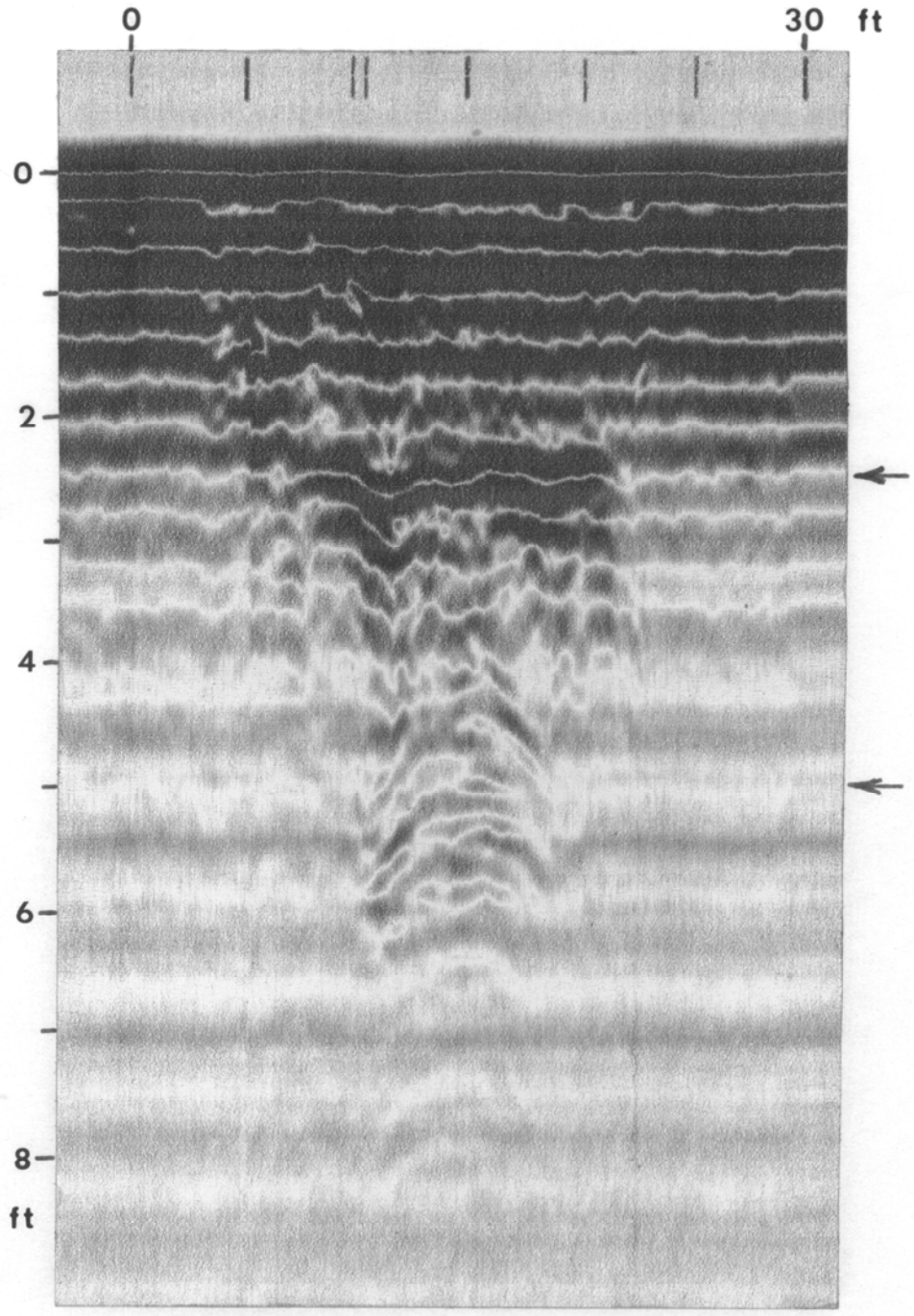

Figure 9: The horizontal bands at a depth of 2.5 ft are the result of an echo from the upper surface of a cavity which was excavated into the earth and covered with wooden boards. The echo from the bottom of this cavity is indicated at an apparent depth of about 5 ft. The actual height of the air cavity was 7.5 ft; since the radar pulse travels about three times faster in air than in the soil, the apparent cavity thickness is reduced.

Frequency: 315 MHz
Pulse velocity: 0.31 ft/ns
Earth resistivity: 50 ohm-meter

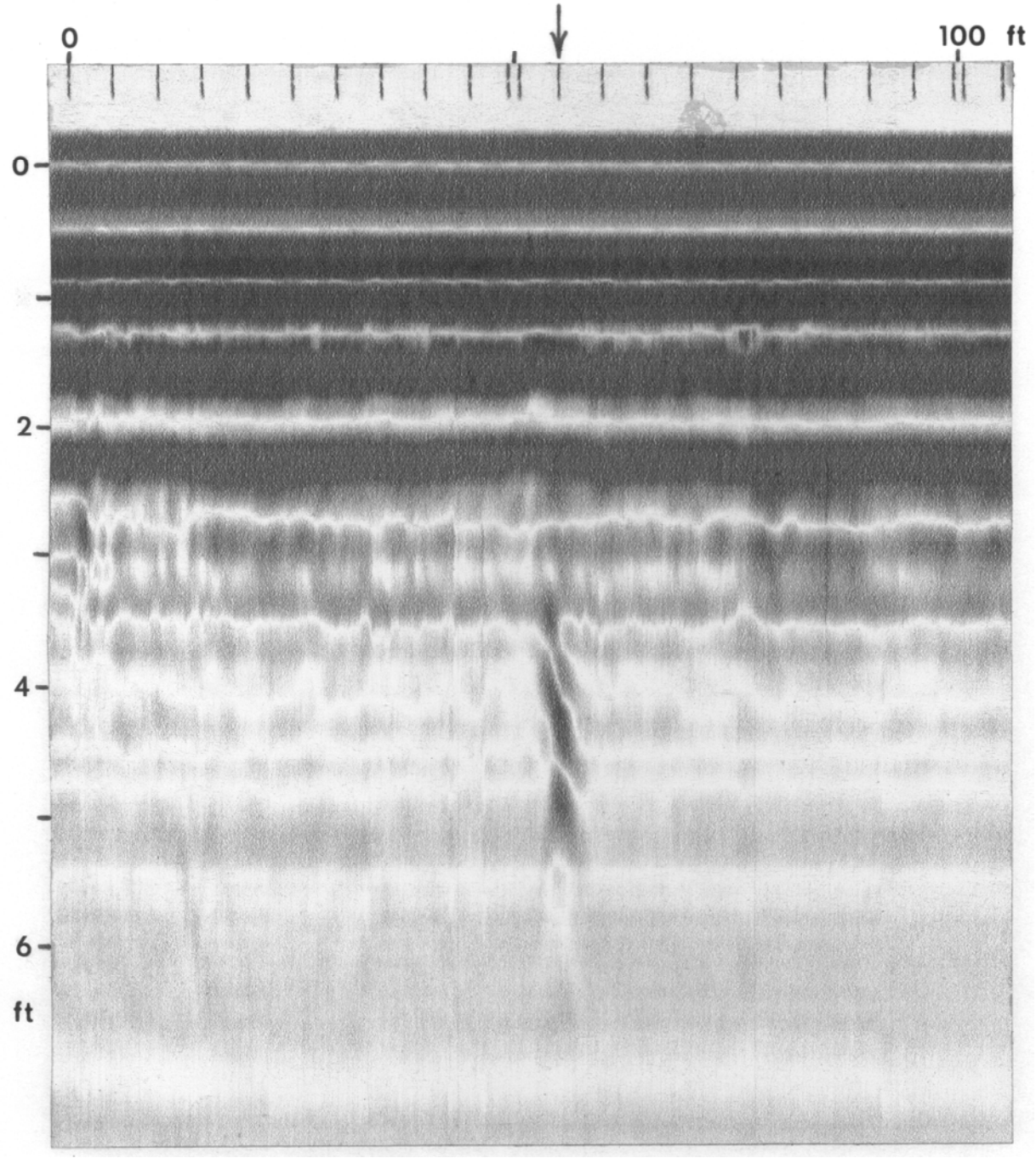

Figure 10: A flat-topped stone caused this echo. It was about four by five feet in size and at a depth of 3 ft.

Frequency: 120 MHz
Pulse velocity: 0.26 ft/ns
Earth resistivity: 40 ohm-meter

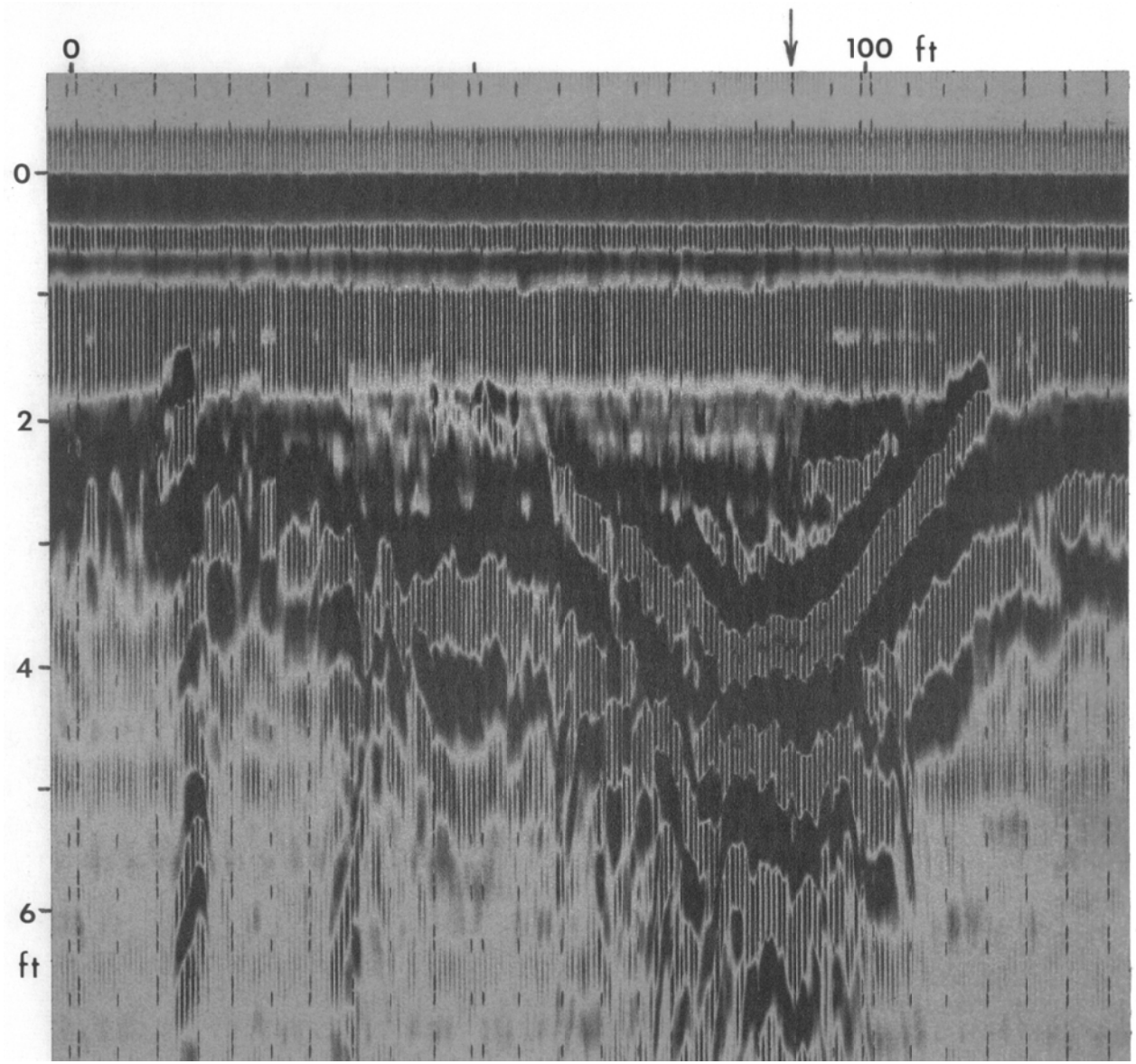

Figure 11: Random stones in the soil or limestone pinnacles could cause the scattered arc patterns on this profile. The stratigraphic basin in the soil is quite shallow and broad; its slope is greatly exaggerated here. The two polarities of the radar echo have been displayed here with different patterns.

Frequency: 120 MHz
Pulse velocity: 0.23 ft/ns
Earth resistivity: 65 ohm-meter

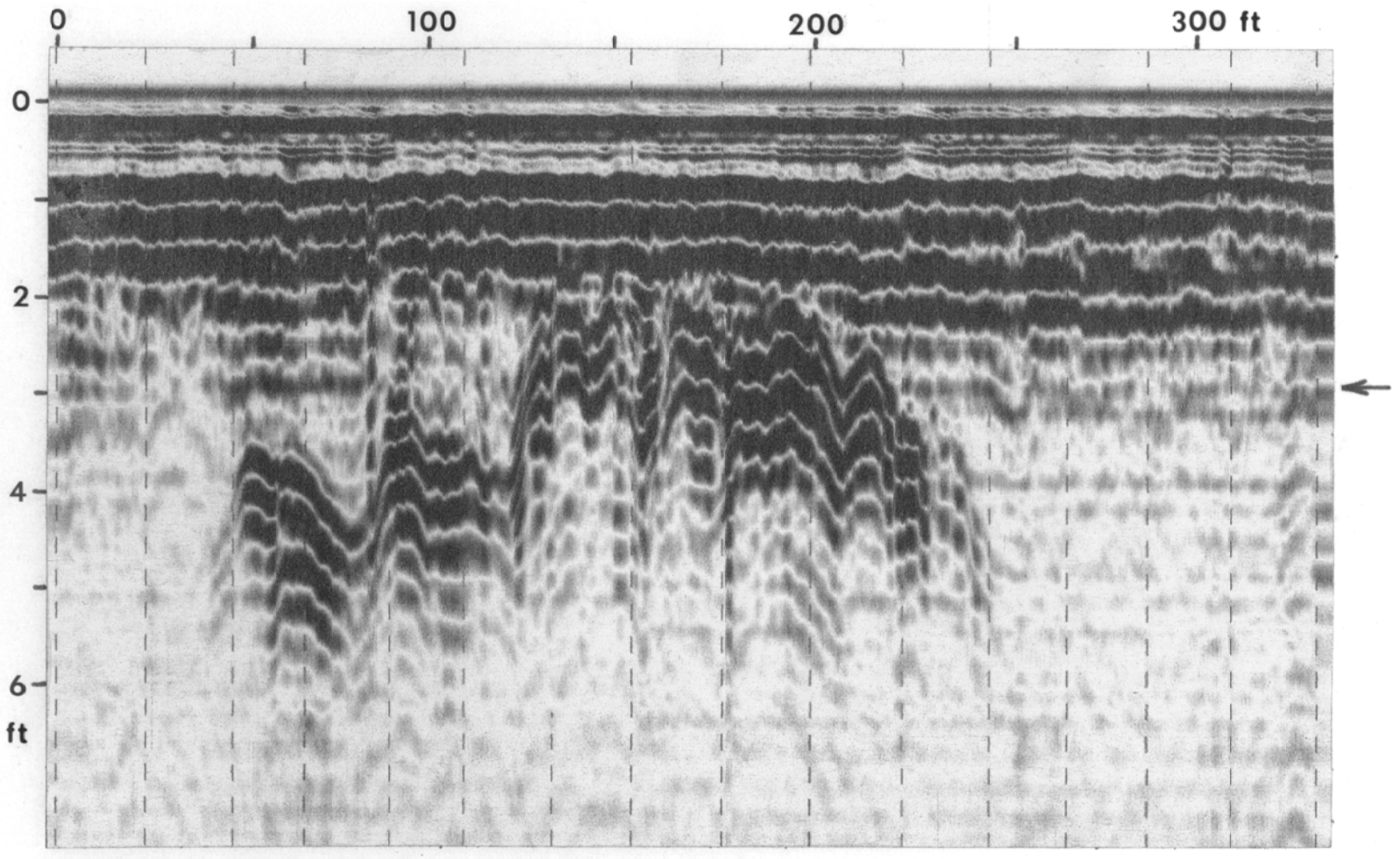

Figure 12: A buried stratum of sandy soil is indicated at a depth of 2 ft to 5 ft on this profile. Silty soil with horizontal stratification overlies it. This profile was made about 75 ft from the area of that in Figure 7.

Frequency: 180 MHz
Pulse velocity: 0.18 ft/ns
Earth resistivity: 100 ohm-meter

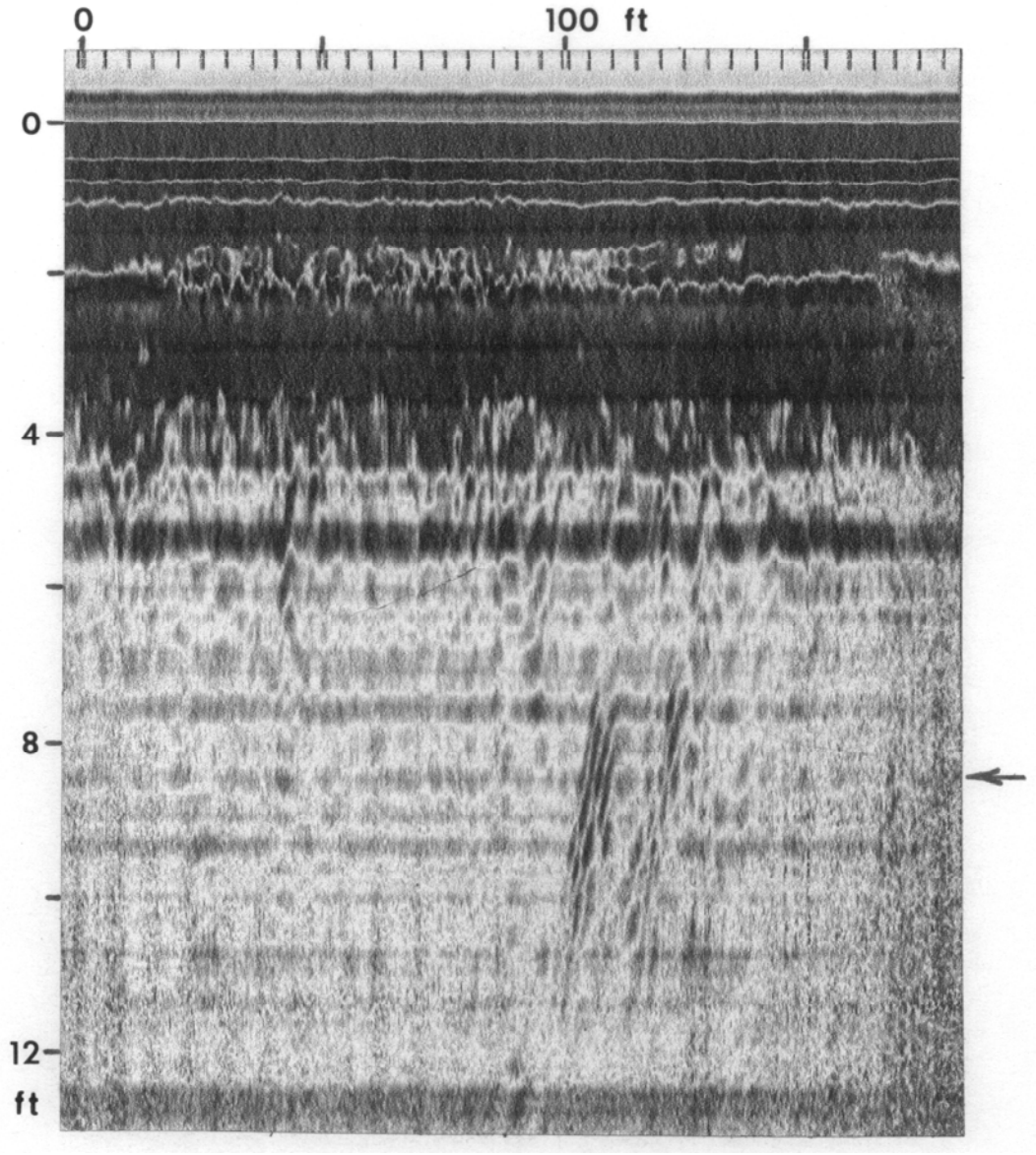

Figure 13: The dipping lines between a depth of 8 ft and 11 ft appear to result from the stratification of decomposed bedrock. While the material is quite earthy, it retains the character of the parent rock, a shaley limestone.

Frequency: 120 MHz
Pulse velocity: 0.25 ft/ns
Earth resistivity: 125 ohm-meter

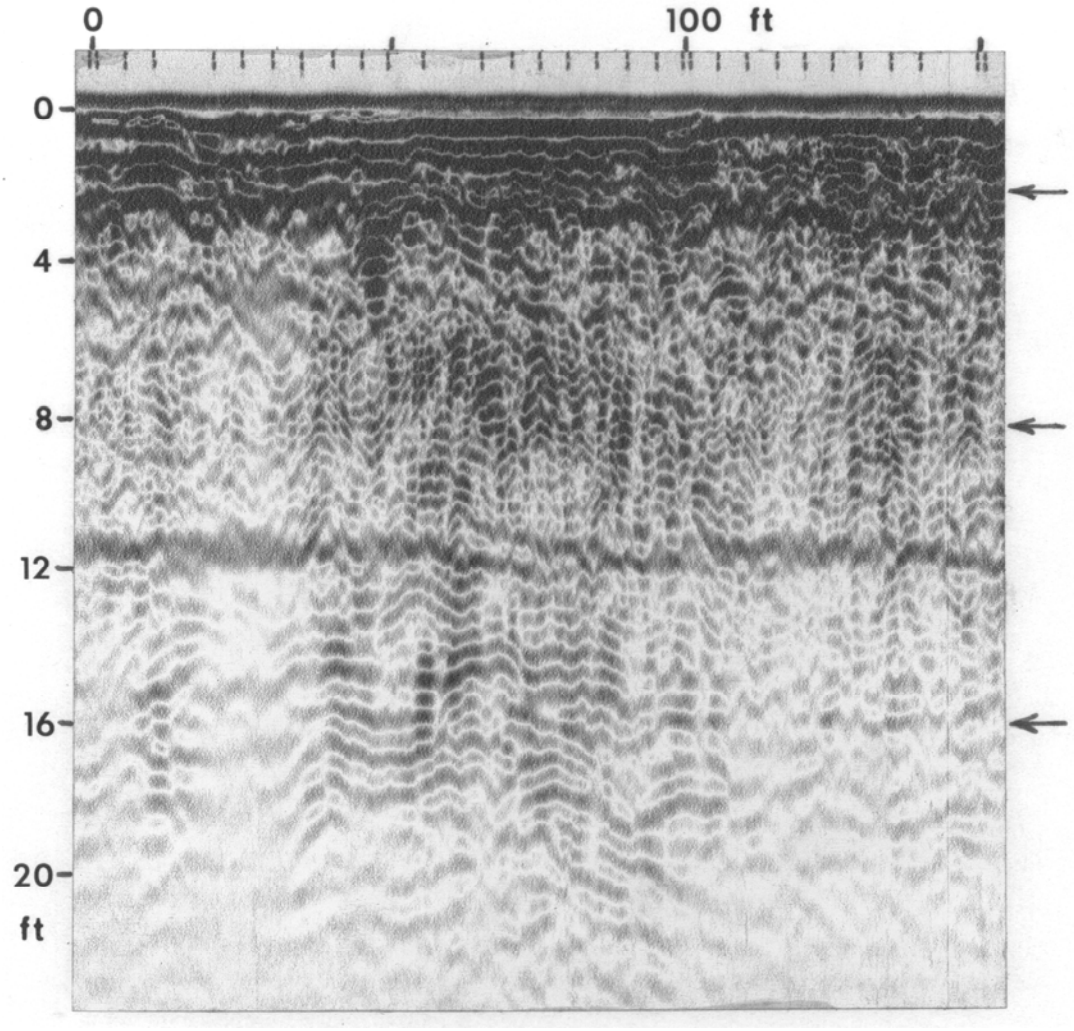

Figure 14: Three different types of soil or rock strata are evident here. The boundaries between these areas are at depths of about 4 ft and 12 ft. The causes of these patterns are not known, although the upper strata are soil and the bottom strata could be bedrock.

Frequency: 180 MHz
Pulse velocity: 0.26 ft/ns
Earth resistivity: Unknown

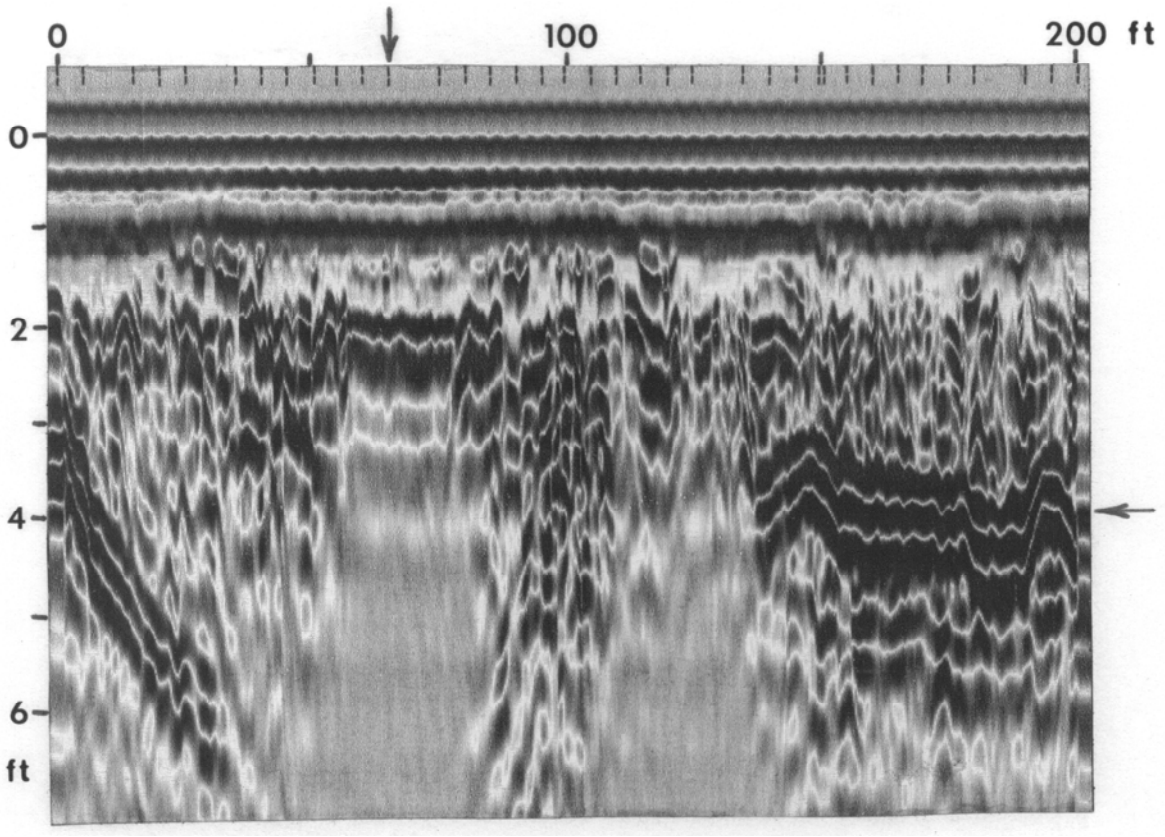

Figure 15: The interface at a depth of 4-6 ft detected by the radar at the ends of this profile is clay under sand. In the area between 55 ft and 75 ft along this profile, a high attenuation surficial layer with a resistivity of about 10 ohm-meter blocks echoes from deeper strata.

Frequency: 120 MHz
Pulse velocity: 0.20 ft/ns
Earth resistivity: 700 ohm-meter (sandy soil) 60 ohm-meter (clayey soil)

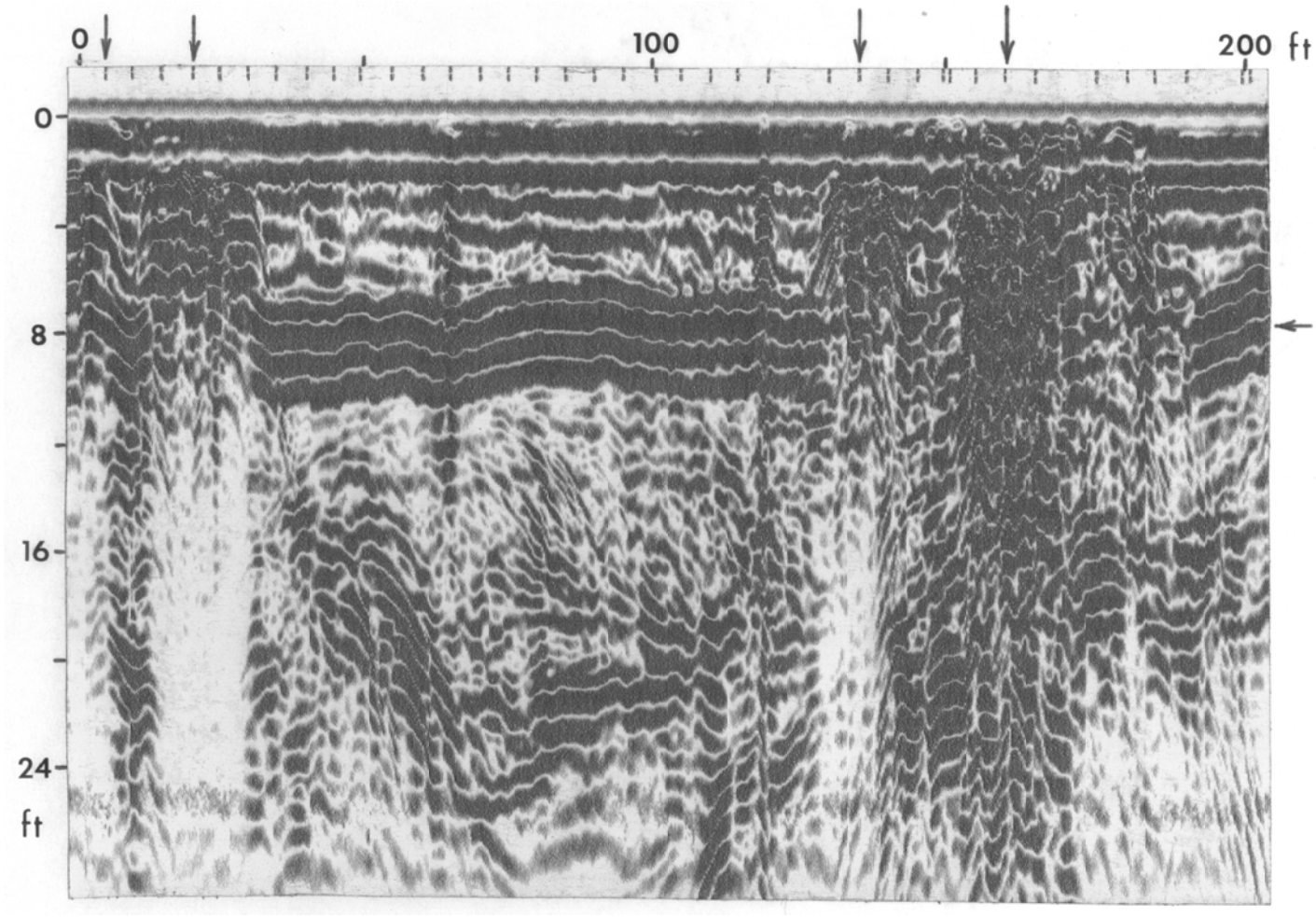

Figure 16: The strong echo at an apparent depth of 8 ft is a reflection from the water table. The soils here are very sandy and the water table is abrupt; it does not appear to have a resistivity contrast. In the vicinity of the 5 ft, 20 ft, and 135 ft points along this profile, near-surface buried material attenuates the radar signal; this material was plastic containers fi11ed with organic chemicals. In the vicinity of the 160 ft point, buried metallic debris causes a complex reverberation of the radar signal.

Frequency: 180 MHz
Pulse velocity: 0.56 ft/ns (above water table)
Earth resistivity: 3000 ohm-meter

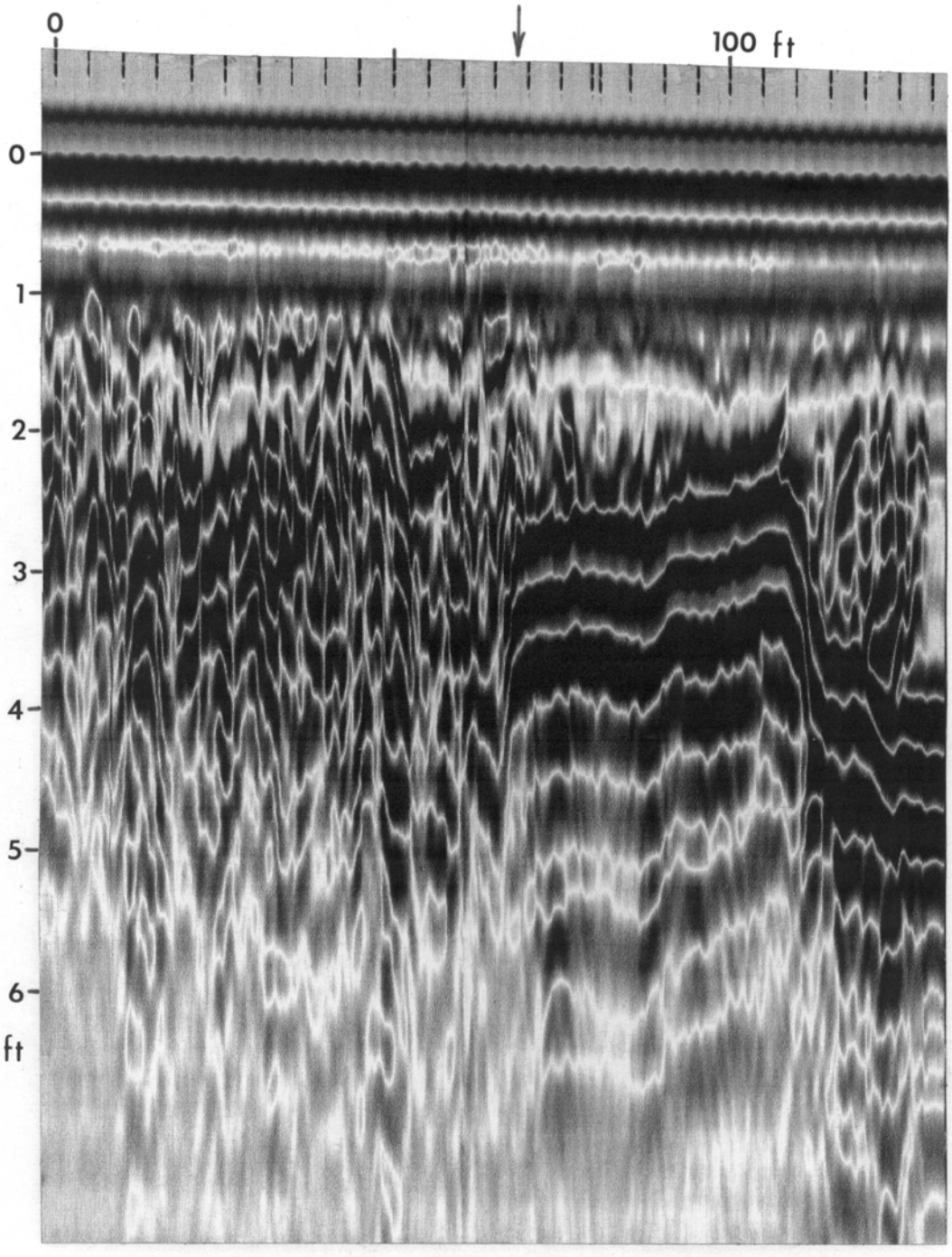

Figure 17: The distinct strata on the right half of this profile are natural. It is likely that buried debris causes the chaotic pattern on the left. The ground surface is flat and does not suggest this buried boundary. This profile is from an area about 100 ft from that in Figure 15.

Frequency: 120 MHz
Pulse velocity: 0.20 ft/ns
Earth resistivity: 60 to 700 ohm-meter

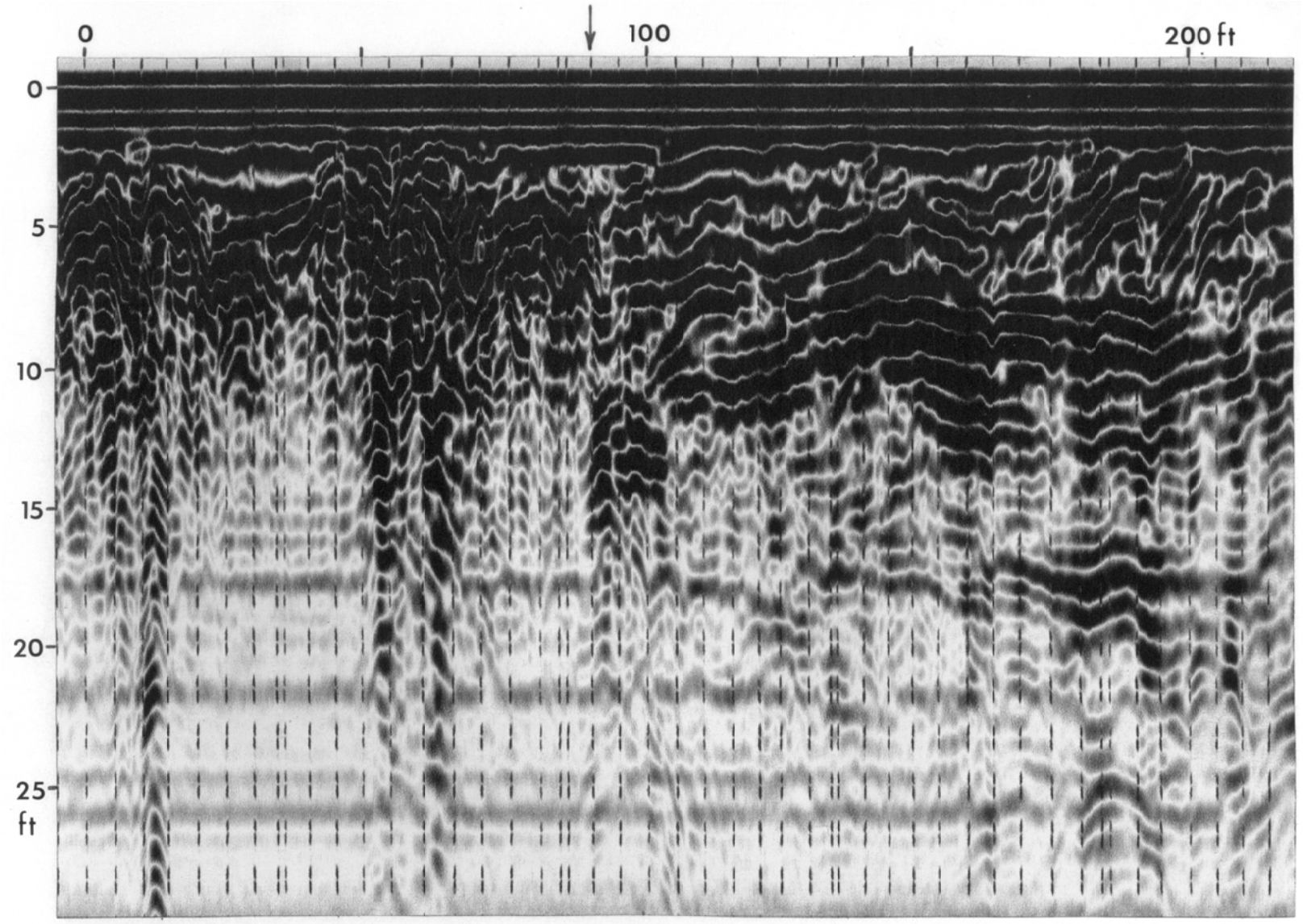

Figure 18: Stratification within this sandy soil is detected to an apparent depth of about 25 ft. The extended echoes to the left of the 90 ft point on the profile are caused by reverberation of the radar signal from landfill debris.

Frequency: 120 MHz
Pulse velocity: 0.45 ft/ns
Earth resistivity: 2000 ohm-meter